ACCIDENTS AT URBAN MINI-ROUNDABOUTS

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1. INTRODUCTION

Mini-roundabouts have been used extensively at urban junctions since their introduction in the early 1970's. They have central islands of up to 4m in diameter, which have no street furniture and are capable of being driven over; they are generally subject to a 30 mph speed limit. In 1994, approximately 1,400 personal injury accidents occurred at mini-roundabouts. Although these numbers are relatively low and there are only a small number of these junctions compared with other junction types, their numbers are increasing rapidly. Therefore it is important that they are designed to be safe. The number of mini-roundabouts was estimated to be about 1600 in the year 1988 and predicted to be about 2500 by the year 1994 as priority junctions were converted to mini-roundabouts and traffic calming became more widespread (Summersgill, 1989; Walker and Pittam, 1989).

This paper outlines some of the results from a recent study of accidents at 3-arm and 4-arm mini-roundabouts on two-way single-carriageway roads in built-up areas (Kennedy et al, 1997). The aim was to determine how accident frequency is related to vehicle and pedestrian flows and to the layout and features of the junction. It was undertaken on behalf of the Road Safety Division of the Department of Transport (DOT) by the Transport Research Laboratory (TRL), with the University of Southampton as a sub-contractor. Accident predictive models have been developed using generalised linear modelling techniques.

The study is one of a series investigating accidents at different junction types including: 4-arm small island and conventional roundabouts (Maycock and Hall, 1984); 4-arm urban traffic signals (Hall, 1986); urban T-junctions (Summersgill et al, 1996); 3-arm urban traffic signals (Taylor et al, 1996); and 4-arm urban priority junctions (Layfield et al, 1996).

2. RECONNAISSANCE AND SITE SELECTION

A reconnaissance survey was undertaken to obtain a representative sample of 200 3-arm and 100 4-arm mini-roundabouts throughout Great Britain. The sample was stratified by vehicle and pedestrian flow. This allowed the effect of variables on accidents to be much more reliably determined than would a purely random sample of the same size.

The junctions had to satisfy the following specific conditions: no double mini-roundabouts; junctions to have 3 or 4 arms; all arms single-carriageway roads with two-way traffic; central islands to be flush or slightly raised circular markings up to 4m in diameter (capable of being driven over and without street furniture); speed limit 30 mph for a distance of at least 100m from the give-way line on all arms; junctions to be in urban areas but not in housing or industrial estates; junctions to be lit; no bus lane on any arm; no major junction within 50m.

3. DATA COLLECTION

The main types of data collected were:

Time-dependent data: surveys of vehicle and pedestrian flows, vehicle queueing, parking occupancy and activity, and vehicle speeds were carried out between 7 am and 7 pm on weekdays excluding school and bank holidays. The flow counts included all turning movements (classified by vehicle type) and each pedestrian crossing movement within 20m of the junction (classified by sex and age). The 12-hour vehicle counts were converted to annual average daily totals (AADTs) using appropriate scaling factors obtained from the DOT. No scaling factors were available for the pedestrian counts.

Geometric data: a comprehensive record was made of junction dimensions, signing and road markings, layout, features, gradients, sight distances and land use. Variables such as vehicle path curvature (deflection), entry radius, inscribed circle diameter, flare length, 'weaving length' and a number of different angles were measured from large scale plans. Deflection was considered to be of particular importance, since entry path curvature has an important effect on accidents at 4-arm roundabouts (Maycock and Hall, 1986); paths for all turning movements which did and did not pass across the central island were included in the current study.

Accident data: records were obtained for the personal injury accidents occurring within 20m of the give-way lines at the 300 selected junctions in the seven year period 1986 to 1992 inclusive. The information included full STATS 19 data from the TRL national database and plain language descriptions from the local authorities. This was used to assign an accident type code and an arm of association to each relevant accident. A few junctions had undergone changes in layout during the accident period; each of these was coded as two separate 'sites'.

4. JUNCTION CHARACTERISTICS

Geographical spread: the distribution of mini-roundabouts is different from that of other junction types in two ways: firstly, mini-roundabouts have been installed extensively in some regions and hardly at all in others; secondly, mini-roundabouts tend to be scattered, appearing in isolation in small towns or on the periphery of larger conurbations.

Central island type: central islands were categorised as follows:

- Flush: smooth white flush central island (no kerb, no dome and not raised above the road surface at the edge or the centre);
- Domed: smooth white domed central island (no kerb, raised above the road surface at the centre);
- Bumpy: central island which is in some sense 'bumpy' (with a noticeably textured surface or edge) and may be domed, or is non-white.

Geometric characteristics:

(i) The central island diameter ranged from 1m to 4.4m and the diameter of the inscribed circle (i.e. the largest circle which will fit within all kerbs) from 8m to 31m;

(ii) Very few arms had more than one lane on the approach, but most had a short flare of less than about 5m with two lanes at the give-way line;

(iii) About one-third of arms had no deflection to the arm which was nearest to straight ahead;

(iv) About two-thirds of the 3-arm sites were T-shaped; the majority of 4-arm mini-roundabouts were cross-roads, although six were K-shaped.

5. ACCIDENT CHARACTERISTICS

5.1 Accident Groups

A total of 1198 personal injury accidents (PIAs) occurred within 20m at the 3-arm sites and 902 at the 4-arm sites over the survey period. The many different accident types initially identified were amalgamated into five main groups (see Table 1): single vehicle accidents, approaching accidents, entering-circulating accidents (sub-divided into crossing and merging accidents), other vehicle accidents and pedestrian accidents. For 4-arm sites, the entering-circulating crossing accidents were further sub-divided into right angle and other crossing accidents. (Right angle accidents cannot occur at 3-arm sites).

Only 17 per cent of accidents at 3-arm and 12 per cent at 4-arm mini-roundabouts were pedestrian accidents. This is higher than at small island (4 per cent) or conventional roundabouts (8 per cent), but only about half the values found for 3-arm and 4-arm junctions respectively in the other urban junction studies (referenced in Section 1).

Fifty six per cent of the *vehicle-only* accidents at 3-arm and 75 per cent at 4-arm mini-roundabouts were entering-circulating accidents. The majority of these accidents at the 4-arm mini-roundabouts were right angle accidents, accounting for 51 per cent of all vehicle-only accidents. This compares with a value of 19 per cent at 4-arm traffic signals and 46 per cent at priority *cross-roads* (excluding staggered junctions). Thus compared to priority junctions and mini-roundabouts, traffic signals have a reduced proportion of right angle accidents but do not eliminate them. About three-quarters of the accidents involving a pedal cycle at mini-roundabouts were entering-circulating accidents; the pedal cycle was most commonly the circulating vehicle.

5.2 Accident Frequency and Severity

Table 2 shows the values obtained in the various junction accident studies for accident frequency and severity. The accident frequency (average number of injury accidents per year) obtained for 3-arm mini-roundabouts (0.92) was intermediate between the value for T-junctions and that for 3-arm signals, whereas the accident frequency at 4-arm mini-roundabouts (1.35) was lower than for other junction types. The accident severity, that is, the percentage of accidents which were fatal or serious, was 12 per cent for 3-arm mini-roundabouts and 14 per cent for 4-arm mini-roundabouts. These were very low compared with those at other junction types.

Table 1: Percentage of accidents by accident group

Accident group	3-arm		4-arm	
	No of PIAs	%	No of PIAs	%
Single vehicle on entry accidents	106	9	66	7
Shunts and side collisions on entry	170	14	66	7
Crossing: Right angle	-	-	*405*	*45*
Other crossing	*422*	*35*	*113*	*13*
Merging:	*134*	*11*	*75*	*8*
Total entering-circulating accidents	556	46	593	66
Other vehicle accidents	165	14	67	8
Total vehicle accidents	997	83	792	88
Total pedestrian accidents	201	17	110	12
Total accidents	1198	100	902	100

5.3 Vehicle and pedestrian flow and accident rate

Table 2 also shows mean flows and accident rates. The average vehicle inflow (AADT) at mini-roundabouts was considerably higher than at priority junctions, with pedestrian flow slightly lower. Traffic signals had much higher values of both vehicle and pedestrian flows. Vehicle flows at 4-arm mini-roundabouts were lower than at conventional and small island roundabouts, but pedestrian flows were broadly similar. These comparisons take no account of the different flow distributions. The proportion of traffic on the minor arm(s) at priority junctions is generally low than at signals or mini-roundabouts.

The mean accident rate (PIAs per 100 million vehicles passing through the junction) observed at 3-arm mini-roundabouts was 12.5, almost identical to that for T-junctions, but somewhat lower than that for 3-arm signals. However, these accident rates take no account of the level of pedestrian flow which also needs to be considered in such comparisons. The rate at 4-arm mini-roundabouts (22.8) was similar to the value at conventional roundabouts, but lower than at other junction types. Rates at 4-arm junctions were much higher than at the equivalent 3-arm junctions.

5.4 Accident Involvement Rates

Table 3 shows the accident involvement rates for different vehicle types (per 100 million vehicles of that type) and the ratios of the involvement rate to the car and light goods vehicle (LGV) involvement rates for each junction type. Involvement rates for pedal cycles and motor cycles were high at all junction types: up to 15 times those for cars and LGVs. The relative involvement rates were lowest at traffic signals and highest at small island and conventional roundabouts. For pedal cycles, they were higher at mini-roundabouts than at traffic signals or priority junctions. For motor cycles, the relative involvement rates at mini-roundabouts were similar to those at priority junctions, with those at traffic signals slightly lower.

Table 2: A comparison of accident frequency, accident rate and severity for different junction types

	Speed limit (mph)	No of sites	No of PIAs	Acc freq (PIAs per site year)	Ave 24 hour veh inflow	Ave 12 hour ped flow	Acc rate (PIAs per 10^8 veh)	Sev (% fatal+ serious)	Years of study
3-arm sites:									
Signals	30	238	2262	1.67	25,730	1,950	17.8	18	1985-1991
T-junctions	30	790	2277	0.58	13,100	1,390	12.1	22	1983-1988
Mini-roundabouts	30	206	1198	0.92	19,974	968	12.5	12	1986-1992
4-arm sites:									
Signals	30	177	1772	2.65	21,180	3,260	34.4	20	1979-1982
Priority junctions	30	233	2440	1.77	15,188	2,056	31.9	22	1984-1989
Small island roundabouts	30-40	25	497	4.38	32,330	1,236[1]	37.1	18	1974-1979
Conventional roundabouts	30-40	11	146	2.36	30,470	1,392[1]	21.2	27	1974-1979
Mini-roundabouts	30	105	902	1.35	16,258	1,442	22.8	14	1986-1992

1 16 hour pedestrian count

Table 3: A comparison of vehicle involvement rates for different junction types

	Number of sites	Pedal cycle	Motor cycle	Car, LGV	HGV	PSV
3-arm sites:						
Signals	238	137 (6)	148 (6)	24 (1)	16 (0.7)	72 (3)
T-junctions	790	95 (6)	123 (8)	16 (1)	9 (0.6)	41 (3)
Mini-roundabouts	206	163 (9)	140 (8)	18 (1)	12 (0.7)	69 (4)
4-arm sites:						
Signals	177	175 (4)	240 (5)	48 (1)	32 (0.7)	126 (3)
Priority junctions	233	177 (4)	358 (7)	48 (1)	20 (0.4)	79 (2)
Small island roundabouts	25	785 (15)	663 (12)	54 (1)	43 (0.8)	62 (1)
Conventional roundabouts	11	291 (13)	267 (12)	22 (1)	18 (0.8)	45 (2)
Mini-roundabouts	105	249 (7)	267 (8)	35 (1)	26 (0.7)	84 (2)

( ) The figures in brackets are the relative involvement ratios (Car, LGV = 1)

6. REGRESSION ANALYSIS

6.1 Method

The objective of the analysis was to relate the accident frequency at the junctions to vehicle and pedestrian flow, and to junction characteristics. The statistical method used was a form of multiple regression analysis and is the same as that employed in the other accident studies (see for example Summersgill et al, 1996; Maher and Summersgill, 1996).

The set of 'explanatory' or 'independent' variables of the regression are functions of the vehicle and pedestrian flows, and the site, geometric and other characteristics of the junctions. Since, however, the numbers of accidents in a given period do not follow a normal distribution and, in particular, do not have a constant variance, the 'generalised linear modelling' technique, available for example in the computer program GENSTAT (Alvey et al, 1977), has been used instead of classical least squares regression. This allows the dependent variable to be drawn from one of a family of distributions.

The regression modelling was undertaken in three main stages:

(i) relating total accident frequency at the junctions (and vehicle-only and pedestrian accident frequencies) to various functions of the vehicle and pedestrian flows and key site features (*total junction accident models*);

(ii) relating accident frequency on each *arm* of the junction for each of the main accident groups to various functions of the flow and site features (*accident group models*);

(iii) extending the best accident-flow models of (ii) using the full range of geometric variables and features observed.

6.2 Form of the Models

The basic form of the model relating accident frequency to flow that has been successful in other TRL junction studies is:

$$A = k\, Q_a^{\alpha}\, Q_b^{\beta} \qquad (6.1)$$

where A is the accident frequency; Q_a and Q_b are functions of the vehicle and pedestrian flows; k, α and β are parameters to be estimated. Before fitting, the model was transformed to linear form by taking logarithms.

Model (6.1) was extended to include non-flow variables. Discrete variables, for example site features, were used at all stages. Continuous variables, for example flow proportions and geometric variables, were included at stage (iii):

$$A = k\, Q_a^{\alpha}\, Q_b^{\beta} \exp \{ \Sigma\, d_{ij} D_{ij} + \Sigma\, g_i G_i \} \qquad (6.2)$$

where A, Q_a, Q_b are as for equation (6.1); D_{ij} (j = 2, n) are dummy variables (taking only the values 0 and 1) representing the 2nd to nth level of each discrete variable; G_i are continuous variables; and k, α, β, b, d_{ij}, and g_i are parameters to be estimated. Accidents increase or decrease with increasing values of G_i according to the sign of g_i.

7. FLOW MODELS FOR TOTAL JUNCTION ACCIDENTS

7.1 Vehicle-Only Accidents at 3-Arm Mini-Roundabouts

This is an example of a total junction accident model. The preferred flow function was the total vehicle inflow at the junction, QT, which includes all flows, but takes no account of their distribution. QT can readily be obtained for T-junctions and 3-arm signals, but was a poor fit at T-junctions, where most of the traffic is on the major road. The preferred model for T-junctions included the total major road and minor road inflows raised to separate powers. Such a function cannot easily be obtained for mini-roundabouts: even where they were converted from priority junctions, the designation of arms as 'major' and 'minor' was not always straightforward, with the 'minor' arm not necessarily that with the lowest flow or at right angles to the other two arms. Thus a function which fits relatively well at all three junction types, for example the sum of the encounter flow products, QN, is a better basis for comparison:

$$A = 0.0570\ QN^{0.581} \qquad (7.1)$$

where A is the vehicle-only accident frequency. Figure 1 compares this accident frequency as a function of QN for 3-arm junctions over a suitable flow range; it shows that T-junctions have a somewhat higher accident frequency than mini-roundabouts or signals.

7.2 Pedestrian Accidents at 3-Arm Mini-Roundabouts

This is a further example of a total junction accident model. The preferred flow function was the sum of the vehicle and pedestrian flow products on each arm, QPW, which fits well at all three junction types:

$$A = 0.0374\ QPW^{0.636} \qquad (7.2)$$

where A is the pedestrian accident frequency at the junction. Figure 2 shows that the pedestrian accident frequency at 3-arm mini-roundabouts is much lower than that at T-junctions or signals.

8. FULL ACCIDENT FLOW GEOMETRY MODELS FOR ACCIDENT GROUPS

8.1 Entering-Circulating Crossing Accidents at 3-Arm Mini-Roundabouts

This is an example of an arm-based accident group model which includes both flow and geometric variables. Entering-circulating crossing accidents arise from the conflicts between right-turning vehicles (i.e. those taking the second exit) from the current arm (arbitrarily labelled as arm 1) and vehicles circulating past that arm. The full model was:

$$A = 0.119\ Q23^{0.514}\ QC^{0.570}\ L_1\ L_2\ L_3 \qquad (8.1)$$

where A is the accident frequency on arm 1; Q23 is the sum of the right turn and U-turn flows entering on arm 1; QC is the flow circulating past arm 1 and L_1, L_2 and L_3 are multipliers.

$L_1 = \exp(5.41\ PWQC)$ where PWQC is the proportion of pedal cycles and motor cycles in QC.

L_2 = exp (0.0529 WEG1 - 0.149 DX1) where WEG1 is the width of entry along the give-way line and DX1 is the distance from the point D1 to the point X2 (see Fig 3).

L_3 = exp (-18.6 IVC503 - 0.0539 GDF3) where IVC503 is an inverse function of sight distance to the right from the previous arm (arm 3) at 50m and GDF3 is the mean percentage gradient from 50m to 100m on arm 3.

Accident risk increased with Q23, $\overline{QC}$, PWQC and WEG1, but decreased with DX1, IVC503 and GDF3. Because accident risk decreased with *inverse* sight distance, a longer sight distance to the right from the previous arm was associated with higher risk. Downhill gradients on the approach on arm 3 were also associated with higher risk.

Apart from flow, the variable found to have most effect on these accidents over its range was DX1. At a symmetric mini-roundabout, all arms have similar values for DX1, but at a T-shaped mini-roundabout, DX1 is largest, and thus accident frequency for this group is lowest, on the 'major left' arm (as viewed from the minor arm).

8.2 Entering-Circulating Right Angle Accidents at 4-Arm Mini-Roundabouts

This is a second example of an arm-based accident group model. These accidents involve collisions between a vehicle going ahead from the current arm (arm 1) and a vehicle going ahead from the previous arm (arm 4). The full model was:

$$A = 0.0975\ Q2^{0.413}\ Q14^{0.479}\ L_1 L_2 L_3 \qquad (8.2)$$

where A is the accident frequency for arm 1; Q2 is the ahead flow from arm 1; Q14 is the ahead flow from arm 4; and L_1, L_2 and L_3 are multipliers.

L_1 = exp (0.113 CK1 - 0.113 DISP4 - 9.58 IVC504) where CK1 is the distance from the island centre C to the nearest point of the kerb K1; DISP4 is the minimum distance from C to the projected centre line tangent at A4 (see Fig 4); and IVC504 is an inverse function of the visibility to the right from 50m back on arm 4.

L_2 = exp (0.499 LON - 1.47 PZC14 - 0.980 NMJ1) where LON, PZC14 and NMJ1 take the value 1 to indicate respectively: location in Greater London; the presence of a pelican or zebra crossing within 20m on arm 1 or arm 4; and the presence of a major junction within 200m on arm 1, and are zero otherwise.

L_3 = exp (-0.0269 ANHS1 - 0.0228 ANHS2) where ANHS1 is the absolute difference of the total angle between tangents at A1 on arm 1 and A3 on arm 3 and 180 degrees, and ANHS2 is the absolute difference of the total angle between tangents at A2 and A4 and 180 degrees (see Fig 4).

Accident risk increased with CK1 and LON, but decreased with DISP4, IVC504, PZC14, NMJ1, ANHS1 and ANHS2. A longer sight distance to the right from the previous arm was again associated with higher risk. The variable CK1 is a measure of inscribed circle diameter.

The angular displacement variables ANHS1 and ANHS2 in L_3 can be replaced by vehicle path curvatures. Since the latter are more difficult to measure and gave a slightly worse fit, a model with path curvatures is chiefly of interest for comparison with entering-circulating accidents at 4-arm conventional roundabouts (Maycock and Hall, 1984). In both cases, arms with greater deflection had fewer accidents; the measurement used at mini-roundabouts was made at the centre of the junction rather than on entry, reflecting the more compact nature of mini-roundabouts.

9. SUMMARY AND CONCLUSIONS

Some of the key findings of the study are listed below.

(i) In general, the mean severity of accidents at mini-roundabouts was much lower than at priority junctions or at signals. Pedestrian accidents formed a low proportion of the total at mini-roundabouts, about half that at priority junctions or signals.

(ii) Accident involvement rates were much higher for two-wheelers than for cars and light goods vehicles. The relative rates for pedal cycles were higher at mini-roundabouts than at priority junctions, whilst those for motor cycles were similar at both types of junction. Traffic signals had the lowest relative involvement rates for pedal cycles and motor cycles. Vehicle proportion variables were included in the models where significant.

(iii) The type of central island did not appear to affect accidents, with the exception of single vehicle accidents at 4-arm mini-roundabouts, for which accident risk was higher at junctions with a domed island than at those with a flat or 'bumpy' island.

(iv) None of the methods for identifying 'major' and 'minor' arms for comparison with priority junctions were entirely satisfactory, especially for 3-arm mini-roundabouts, and therefore arm-based models have been developed for accident groups.

(v) Deflection was important for right angle accidents at 4-arm mini-roundabouts, but could be represented by angular displacement variables rather than vehicle path curvatures.

(vi) Visibility was a key variable affecting a number of different accident groups, with the effect that accidents increased with longer sight distances.

(vii) None of the speed variables tested were significant in the final models. This study was not intended nor designed to investigate speed mechanisms and relationships in depth, and only coarse measures of speed were included. Traffic calming measures such as speed humps, speed cameras and chicanes were not tested in the study.

The models are intended to be used to identify potential design improvements and to provide accident estimates for the economic appraisal of road improvements. In conjunction with traffic assignment models, they can be used: to predict the effect on accidents of traffic management schemes; to identify casualty-reducing strategies; and to optimise safety/mobility for all road users.

10. ACKNOWLEDGEMENTS

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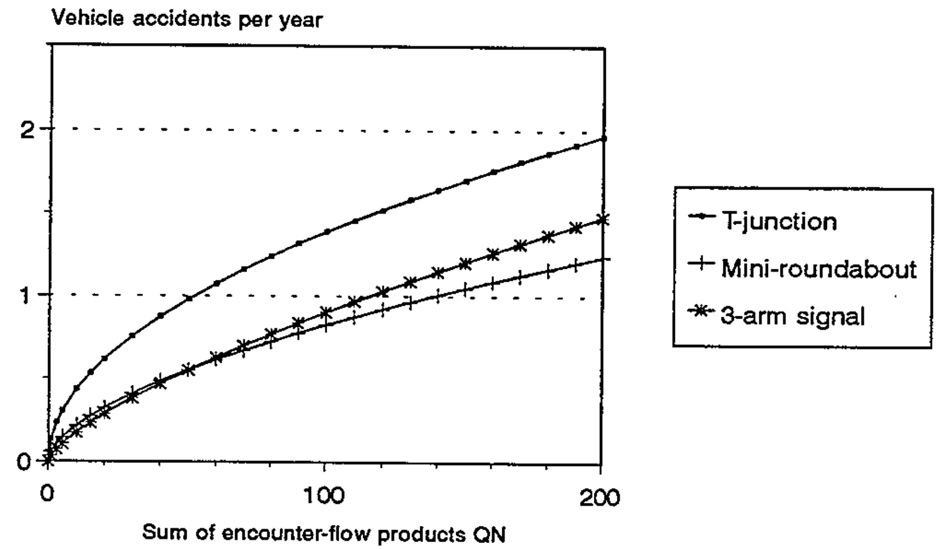
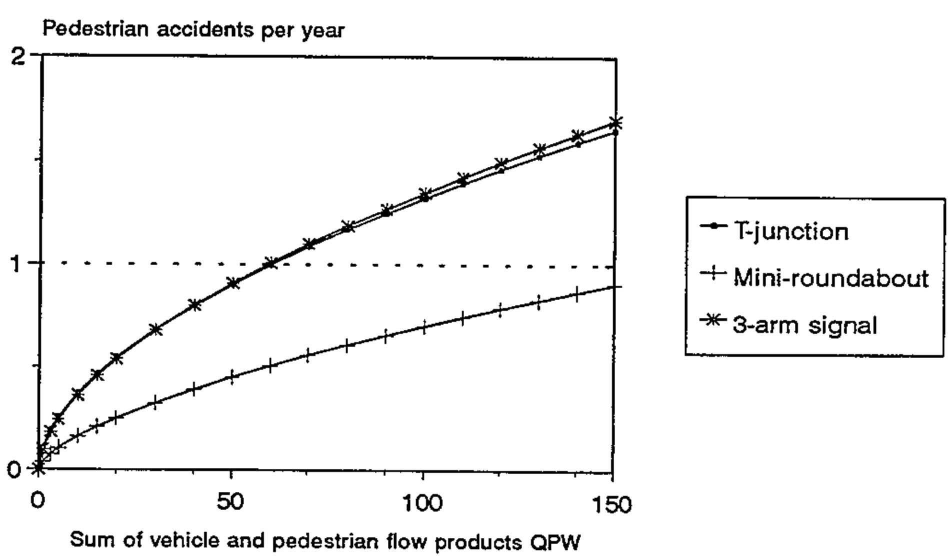
Fig 1: Comparison of predicted vehicle accident frequency at 3-arm junctions



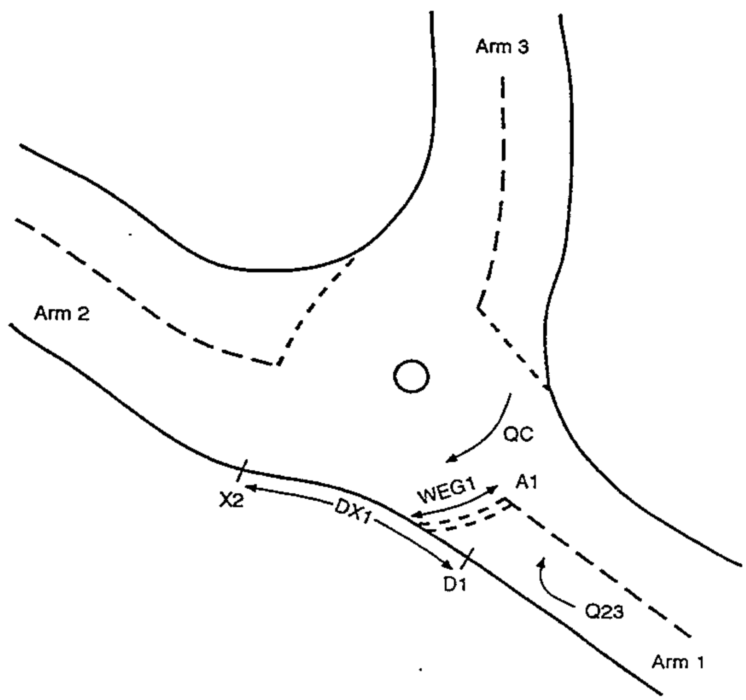
Includes T-junctions on 40 mph roads
QN is in millions

Fig 2: Comparison of predicted pedestrian accident frequency at 3-arm junctions



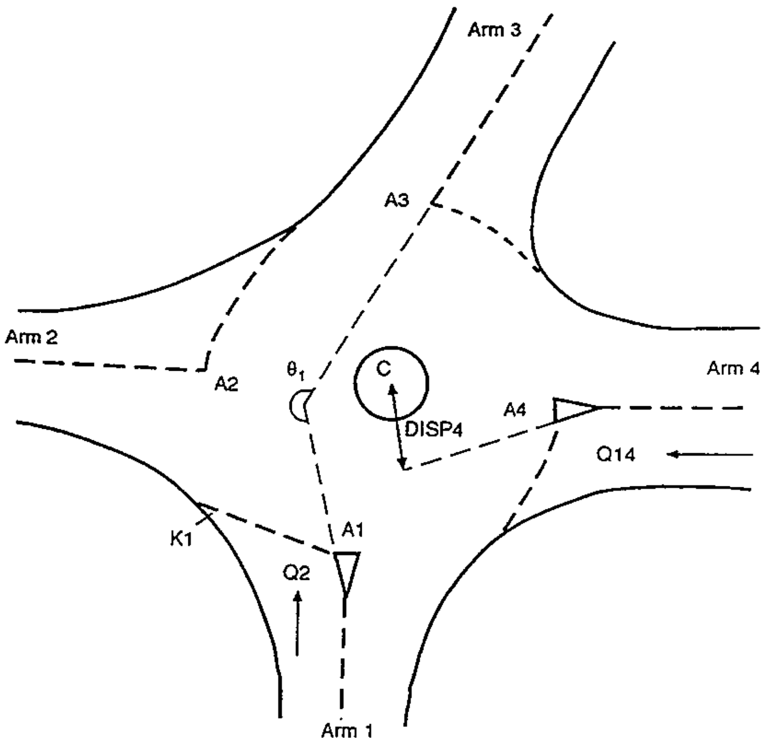
Includes T-junctions on 40 mph roads
QPW is in millions

Fig 3: Entering-circulating crossing accidents at 3-arm mini-roundabouts



Q23	is the sum of the right turn and U-turn flows on the arm of interest (arm 1), in thousands;
QC	is the flow circulating past arm 1, in thousands.
PWQC	is the proportion of two-wheelers in QC;
A1	is the point where the give-way line on arm 1 meets the centre road marking or island;
D1	is the point on the entry kerb from which a perpendicular would meet A1;
X2	is the equivalent point to D1 on the exit side of arm 2;
WEG1	is the width of entry measured along the give-way line from A1 to the kerb (m);
DX1	is the distance from D1 to X2, measured along the kerb (m);
IVC503	is an inverse function of sight distance to the right from arm 3 at 50m;
GDF3	is the percentage gradient from 50m to 100m on arm 3 (negative for downhill towards the junction, positive otherwise).

Fig 4: Entering-circulating right angle accidents at 4-arm mini-roundabouts



Q2	is the ahead flow on the arm of interest (arm 1), in thousands;
Q14	is the ahead flow on the previous arm (arm 4), in thousands.
C	is the centre of the central island;
K1	is the point on the entry corner kerb of arm 1 that is closest to C;
CK1	is the distance from C to K1 (m);
An	is the point where the give-way line on arm n meets the centre road marking or island;
DISP4	is the minimum distance from C to the projected centre line tangent at A4 (positive if the tangent is to the left of C, negative otherwise - the positive case is illustrated) (m);
IVC504	is an inverse function of sight distance to the right from arm 4 at 50m;
ANHS1	is $\lvert 180° - \theta_1 \rvert$, the absolute value of the difference between 180 degrees and the angle of arm 1 with arm 3, measured clockwise between the centre line tangents at A1 and A3;
ANHS2	corresponds to ANHS1 between arms 2 and 4;
LON	is location in central London; PZC14 is the presence of a pedestrian crossing within 20 on arm 1 or arm 4; NMJ1 is the presence of a major junction within 200m on arm 1.